

# Optical Communications Study for the Next Generation Space Telescope

Juan M. Cenicerros

## Abstract

The Next Generation Space Telescope (NGST), part of NASA's Origins program, is a follow on to the Hubble Space Telescope expected to provide timely new science along with answering fundamental questions. NGST is a large diameter, infrared optimized telescope with imaging and spectrographic detectors which will be used to help study the origin of galaxies. Due to the large data NGST will collect, Goddard Space Flight Center has considered the use of optical communications for data downlink. The Optical Communications Group at the Jet Propulsion Laboratory has performed a study on optical communications systems for NGST. The objective of the study was to evaluate the benefits gained through the use of optical communication technologies. Studies were performed for each of four proposed NGST orbits. The orbits considered were an elliptical orbit about the semi stable second Lagrangian point, a 1 by 3 AU elliptic orbit around the sun, a 1 AU drift orbit, and a 1 AU drift orbit at a 15 degree incline to the ecliptic plane. An appropriate optical communications system was determined for each orbit. Systems were evaluated in terms of mass, power consumption, size, and cost for each of the four proposed orbits.

## 1. Introduction

The Next Generation Space Telescope (NGST) study was performed to inform Goddard Space Flight Center (GSFC) about optical communication technology. GSFC provided information on each of four proposed orbits for NGST. Using the orbit information, suitable optical communication systems were proposed for each orbit.

The assumed mission scenario consists of a spacecraft in orbit for a period of ten years. Device lifetimes for each of the proposed components meet or exceed this period. A large onboard storage capacity capable of storing a weeks worth of data during probable periods of outage was assumed to ensure that no data is lost through interruption of the downlink signal. A technology freeze was set for 2003. Costing for components is based on 1998 Dollars. Mass, power, and cost estimates rely heavily on data obtained in [3].

Background radiance for each of the cases was found using MODTRAN. The chart which the radiance values were obtained from is given in Appendix A. The units for the background light is  $W/m^2/A/Sr$ .

All link analysis was performed using software produced by the Optical Communications Group at JPL. Free-Space Optical Communications Analysis Software (FOCAS) version 1.08 was used to evaluate each communication link. A margin of 5 dB was used to guard against any uncertainties in the link. The required bit error rate was  $1e-7$ . Once achievable data rates were found, the viewing data provided by Dave Wampler at GSFC was used to generate the data volumes listed.

## 2. L2 Orbit

The first of the orbits evaluated was the L2 orbit. During the lifetime of this orbit the spacecraft (S/C) sits in a halo orbit approximately 0.1 AU away from the earth. Figure 1 gives an illustration of this orbit when looking down the ecliptic plane. For downlink cases the S/C is assumed to always be viewed during the night, resulting in a minimal amount of background noise seen by the ground station. Background for the uplink case is also negligible due to the geometry of orbit, i.e. the sun does not come into the field of view of the S/C aperture as it looks down upon the earth.<sup>1</sup> Hence a background radiance of  $1e-9 W/m^2/A/Sr$ , which corresponds to a nighttime case, was used for all L2 analysis.

Given the short link distance, the modulation scheme which delivers the highest data rate is On-Off Keying (OOK). For this link a solid state laser with a wavelength of 860 nm was chosen. The output power of the laser was 1 Watt.<sup>2</sup> The transmitting aperture aboard the S/C was a 10-cm telescope. The ground station employed the use of a 3-m telescope. Using a link margin of 5 dB, the achievable data rate is 7.8 Mbps for the worst case scenario. Table 1 shows important link

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<sup>1</sup> Private communication with Muthu Jeganathan at JPL.

<sup>2</sup> Private communication with Hamid Hemmati at JPL.

parameters used to determine the data rates available for the L2 orbit. All Sun-Earth-Probe angles throughout this report will be given in degrees, all background radiance in units of  $\text{W/m}^2/\text{A}/\text{Sr}$ , and all data rates in Mbps.

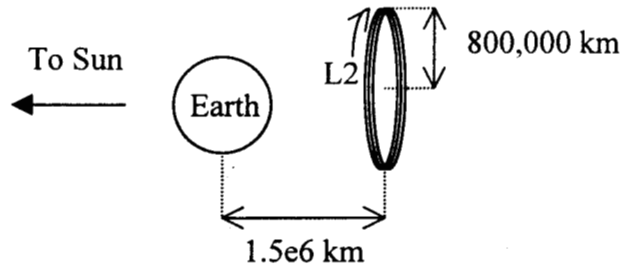


Figure 1. L2 Orbit Geometry (from Michael Mesarch at GSFC)

To determine the available data volume for the L2 case the achievable data rate is multiplied by the viewing time per day. The worst case viewing time for the S/C while in the L2 orbit is 226 minutes per day. Using this viewing time and a worst case link scenario, a daily data volume of roughly 106 Gbit/day is possible. Further orbit analysis is necessary to determine the orbital data volume variation. The biggest factor that contributes to the data volume is the viewing time per day, as the data rates do not vary drastically throughout the orbit of the S/C.

	Distance (km)	SEP Angle (Degrees)	Background Radiance ( $\text{W/m}^2/\text{A}/\text{Sr}$ )	Data Rate (Mbps)
Best Case	1.50e6	180	1e-9	11.1
Worst case	1.75e6	180	1e-9	7.8

Table 1. L2 Orbit Parameters

### 3. 1 AU Drift (Ecliptic Plane)

The second orbit analyzed was the 1 AU drift orbit in the ecliptic plane. During the lifetime of this orbit, the S/C starts off close to the earth, and floats away at a rate 0.1 AU per year for a period 10 years. Thus, the distance between the earth and the S/C is 1 AU at the end of the mission. Table 2 shows the orbital parameters and the orbital data rate variation for this orbit.

Due to the length of the link in the latter stages of the orbit, Pulse Position Modulation (PPM) is a more efficient scheme than OOK. The chosen alphabet size of the PPM word is 256. For this link a Nd:YAG cavity dumped laser with an operating wavelength of 1064 nm was chosen. The output power of the laser was 3 Watts, with a pulse width of 10 nsec. The minimum allowable dead time for the laser is 1 usec.<sup>2</sup> The transmitting aperture aboard the S/C was a 30-cm telescope. The ground station for this case consists of a 10- m telescope. The achievable data rates are listed in Table 2 are those obtained for a link margin of 5 dB. Link distance in Table 2 is given in AU.

Due to the minimum allowable dead time of 1usec, the highest data rate achievable with a PPM 256 modulation scheme is 1.673 Mbps. For the PPM 256 scheme suggested with a slot width of 12.5 nsec and a dead time of 1 usec the total word time is 4.2 usec. Since there are  $\log_2 M$  bits in each word the bit rate is about 1.9 Mbps. The use of a Reed-Solomon error correcting code drops the data rate to 1.67 Mbps. This is the data rate for years 1 through 7. After much consideration it was decided that a scheme employing various sizes of PPM words (i.e. switching from PPM 32 to PPM 64 for example) would not be prudent during flight.<sup>1</sup>

Best case and worse case scenarios can be obtained by simply taking a single launch period and using the best case and worst case link distances. Using the fall case when the S/C is close to the earth (i.e. year 1) coverages range from 324 minutes to 651 minutes, corresponding to data volumes of 32.5 Gbit/day and 65.3 Gbit/day. Towards the end of the mission (i.e. year

10) these coverages correspond to data volumes of 19.4 Gbit/day to 39.1 Gbit/day. The average over the lifetime of the mission is 47.8 Gbit/day. To boost the data rate two lasers can be used to transmit data, one with a right hand circularly polarized beam, and one with a left hand circularly polarized beam. This strategy will effectively double the data rate from that listed above. The two circular polarizations are achieved by passing the output beam of each laser through the appropriate polarizer.

Year	Distance (AU)	SEP Angle (Degrees)	Background (W/m <sup>2</sup> /A/Sr)	Data Rate (Mbps)	Margin (dB)
1	0.1	90	0.00209	1.67	23.06
2	0.2	84	0.00216	1.67	16.98
3	0.3	81	0.00223	1.67	13.40
4	0.4	78	0.00230	1.67	10.84
5	0.5	75	0.00237	1.67	8.85
6	0.6	72	0.00239	1.67	7.25
7	0.7	69	0.00240	1.67	5.90
8	0.8	66	0.00242	1.57	5.0
9	0.9	63	0.00244	1.23	5.0
10	1.0	60	0.00245	1.00	5.0

Table 2. Orbital Information for 1 AU Drift Orbit in Ecliptic Plane.

The use of a single ground station does not meet the 100 Gbit/day link requirement for this orbit. The use of two ground stations will boost worst case and best case viewing times to 845.5 minutes and 899.5 minutes respectively. Data volumes at the end of the mission for a single laser transmitter are thus 50.7 Gbit/day and 54 Gbit/day with an average of 82 Gbit/day. The use of two circularly polarized beams will increase the end of mission data volumes to 101.4 Gbit/day for the worst case viewing time and 108 Gbit/day for the best case viewing time. Using two ground stations the average for the mission is 164 Gbit/day.

#### 4. 1 AU Drift 15 Degrees to Ecliptic Plane

Another drift orbit analyzed was the 1 AU drift orbit at an incline of 15 degrees with respect to the ecliptic plane. Similar to the previous drift orbit the S/C starts off close to the earth, and floats away at a rate 0.1 AU per year for a period 10 years. The distance between the earth and the S/C is a little more than 1 AU at the end of the mission, due to the S/C being outside the ecliptic plane. Due to the similarity of the two drift orbits, the values seen in Table 2 were used to obtain the daily data volumes.

The S/C aperture is 30-cm, the ground station is 10-m telescope, and the laser is a 3 Watt Nd:YAG modulated with PPM 256 as was the case for the other drift orbit. The key difference between the drift orbit at a 15 degree incline to the ecliptic plane and the drift orbit contained in the ecliptic plane is the amount of time ground stations are able to see the S/C. Due to the nature of the orbit, a single ground station is far too ineffective, and will not be considered. All analysis for this orbit made use of two ground stations. For a fall launch, worst case and best case viewing times are 709.5 minutes and 1440 minutes respectively, when using two ground stations. Thus, worst case and best case data volumes achievable at the end of the mission are 42.5 Gbit/day and 86.4 Gbit/day. The average throughout the life of the mission is 80.4 Gbit/day. Employing right hand and left hand circularly polarized beams increases the end of life worst case data volume to 85 Gbit/day and the best case data volume to 172.8 Gbit/day. The average data volume available with two beams is 160.8 Gbit/day.

#### 5. 1X3 AU Orbit

The final orbit considered for NGST was a 1X3 AU orbit around the sun. For this orbit the S/C can be as far as 4 AU away from earth, making downlink communication difficult. More important is the fact that the SEP angle is smaller than ten degrees for several periods of time. Figure 2 shows the SEP angle throughout the life of the mission.<sup>3</sup> Due to the large amount of power radiated by the sun, a 10-m ground station can not track the S/C when the SEP angle is less than 10 degrees. The result is seven periods of outages. Using the figure to estimate the length of the outages, we see there are five different time frames when downlink is unavailable for roughly 37 days, one outage period of 46 days, and one lengthy period of unavailability for about 243 days beginning at day 3000.

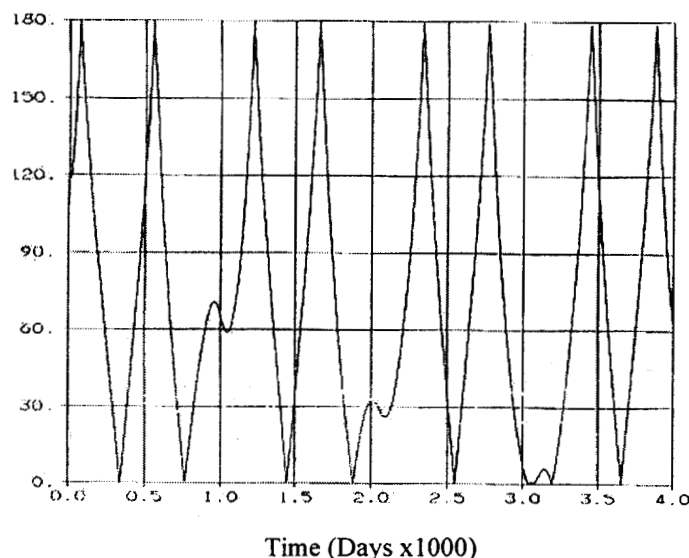


Figure 2. Sun-Earth-Probe angle versus time.

The technology used for the 1X3 AU orbit is the same as that used for the two drift orbits. A 30-cm S/C aperture was used in conjunction with a 10-m ground station and a 3 Watt Nd:YAG pulsed laser with a PPM 256 modulation scheme. Table 3 shows the achievable data rate for a single laser transmitter throughout the life of the mission in half-year increments. Outage periods are denoted in Table 3 by the symbol 'NA' for periods when a communication link is not possible due to an SEP angle of less than 10 degrees. The distance is given in AU.

Time (yrs)	Distance (AU)	SEP Angle (Degrees)	Data Rate (Mbps)	Margin (dB)	Time (yrs)	Distance (AU)	SEP Angle (Degrees)	Data Rate (Mbps)	Margin (dB)
0.5	1.5	80	0.459	5.0	5.5	2.0	32	0.204	5.0
1.0	2.0	20	0.648	5.0	6.0	2.0	45	0.235	5.0
1.5	3.5	180	0.053	5.0	6.5	1.7	120	0.357	5.0
2.0	2.0	35	0.212	5.0	7.0	4.0	5	NA	NA
2.5	1.75	60	0.327	5.0	7.5	2.0	150	0.258	5.0
3.0	1.2	65	0.698	5.0	8.0	2.7	45	0.129	5.0
3.5	2.0	115	0.258	5.0	8.5	2.0	0	NA	NA
4.0	3.8	0	NA	NA	9.0	2.6	25	0.139	5.0
4.5	2.0	180	1.23	5.0	9.5	1.8	120	0.319	5.0
5.0	3.2	40	0.089	5.0	10.0	4.0	15	0.046	5.0

Table 3. Achievable data rates for 1x3 AU Orbit.

Using the viewing information provided by Dave Wampler for a single ground station, the best case data volume at the beginning of the orbit (0.5 yr.) is 25.4 Gbit/day while the worst case data volume for this time period is 12.6 Gbit/day. At the

<sup>3</sup> Sun-Earth-Probe angle information generated by Elliott Cutting at JPL.

end of the mission the worst and best case available data volumes are 0.894 Gbit/day and 1.8 Gbit/day. The average data volume throughout the course of the mission is 7.26 Gbit/day.

Using two ground stations the worst case and best case data volumes achievable at the beginning of the orbit are 33.5 Gbit/day and 35 Gbit/day. At the end of the orbit the achievable volumes are 2.37 Gbit/day and 2.49 Gbit/day. The average throughout the mission is 12.2 Gbit/day. The use of two lasers and two ground stations can only support an average downlink of 24.4 Gbit/day.

## 6. Uplink

The uplink data volume of 8 Mbit/day can easily be achieved for every orbit, with the exception of the 1X3 AU orbit. Uplink for the 1X3 orbit is possible, but extremely high laser power is required. The uplink system will consist of a 25-cm ground telescope transmitting light from a Doubled Nd:YAG laser operating at a wavelength of 532 nm. The telescope onboard the S/C serves as both the transmitting and receiving aperture. Due to the difference in wavelength, the S/C may transmit and receive data simultaneously. The receiving aperture is 10-cm for the L2 orbit and 30-cm for each of the other three orbits. The data rate for the L2 orbit is 10 kbps while the data rate for the remaining three is 2 kbps. Thus, the uplink data volume can be achieved in about 15 minutes for the L2 and a little over an hour for all other orbits. Table 4 shows the laser power necessary to obtain the worst case uplink data rates with a link margin of 5 dB.

Orbit	S/C Aperture (m)	Ground Aperture (m)	Laser Power (W)
L2 (worst)	0.1	0.25	0.54
1X3 AU (worst)	0.3	0.25	3865.24
1 AU Drift (worst)	0.3	0.25	663.66
1 AU Inc (worst)	0.3	0.25	681.12

Table 4. Required uplink laser power.

An important note to make is that multiple uplink beams should be used. This is necessary to overcome the effects of scintillation. Eight to sixteen beams will probably be used for the uplink. The total power provided by the multiple lasers should equal the power shown in Table 4.

## 7. Acquisition and Tracking

Prior to establishing a communications link, it is necessary for the ground station and the S/C to perform mutual acquisition of each others beam. This is required for accurate pointing of the transmit signal. Identification of the position of the Earth receiving station to better than 5 to 10% of the downlink signal beamwidth is desired to insure a stable link. Once the position of the receiving station is known the point-ahead angle for the downlink beam can be determined such that the signal from the spacecraft is received by the ground station [3]. The acquisition and tracking for the optical communication system is performed by tracking a laser beacon signal sent by the earth receiving station. If the data rate of the uplink beam is sufficiently high the same laser beam may be used for both the communication link and the acquisition and tracking signal. The power necessary for acquisition and tracking is small, on the order of  $1e-9$  Watts.<sup>5</sup> A simple beam splitter may be used to send a portion of the signal to the acquisition and tracking arm and the majority of the signal to the communications detector. Upon determination of the point-ahead angle the fine steering mirror, which controls the pointing of the beam, is adjusted accordingly.

## 8. Optical Terminals

The design of the telescopes for the S/C and ground receiving station is a basic Cassegrain configuration. The two proposed terminals for the S/C consist of a 30-cm primary aperture with an obscuration of 30% due to the secondary mirror, and a 10-cm primary with an obscuration of 25% due to the secondary. The diameters of the primary mirrors for the ground telescopes are 10-m and 3-m. Each of these telescopes will have an obscuration of 20%. More detailed descriptions of the ground and space telescopes, complete with mass and cost estimates are found in [3].

The ground stations must be located in places where a majority of the days are clear. Proximity to JPL is desirable. Goldstone is one such location. Other locations, which would provide 24-hour coverage together with Goldstone, are Central Australia and South Africa. These three locations are desirable places to build a 10-m ground station. The Telecommunications and Mission Operations Directorate at JPL forecasts the completion of a 10-m station at Goldstone by 2006. There are existing sites in the Southwest United States that could possibly be used as well. For possible leased sites the capability to support daytime operation is a must, together with the ability to support a large instrument package, adequate tracking capability, and the capability to readily transfer data between JPL or GSFC. Existing locations which may meet these criteria are Palomar, CA (5-m), Albuquerque, NM (3.5-m), Hawaii (3.65-m), and Arizona (6.5-m). An existing telescope in the Canary Islands (4.5-m) and a proposed telescope in Chile (8-m) are possibilities, but may prove problematic for daytime operations.<sup>4</sup>

## 9. Availability Schemes

An availability of 98% has been specified for the NGST program. Whereas cloud coverage and rain have little effect on a RF communication system, even the slightest cloud coverage can severely degrade the performance of an optical communication system. To determine the availability for an optical system the percentage of sunny days at the receiving site must be considered. For the deep space network station at Goldstone roughly 70% of the days are sunny. Choosing two other sites with 70% sunny days and assuming that the probability of cloud coverage for each site is independent of the others, an availability of 97.3% is achievable. For the L2 orbit, since only one ground station is required to achieve the desired data volume, three stations will meet the availability constraint.

If multiple stations are needed to achieve the required downlink requirements, the average availability can be determined using the following formula for average daily availability:

$$\langle Avail \rangle = \frac{1}{T} \sum_k Avail_k \cdot t_k$$

Where  $T$  is the amount of coverage necessary each day to achieve the downlink data volume,  $Avail_k$  is the availability of site  $k$ , and  $t_k$  is the amount of time site  $k$  is available each day. The number of sites required for 98% availability can be found in this manner. Availability information and viewing times for proposed optical receiving sites are not available. A further study would be necessary to determine how many sites are needed and where they should be located.

Another alternative for the L2 case is to simply use a single station and derate the data rate by the weather availability factor to account for days when a link is not possible. Given this scheme the storage capacity onboard the S/C would need to be able to hold a larger amount of data to account for days when downlink is not possible. A storage capacity of one week should be sufficient to guarantee that no data is lost. Since the required daily data volume is 100 Gbits, the required storage capacity for this scheme would be 700 Gbits.

## 10. Technology Maturity

Most of the technology used for the optical communications study is currently available. The key items for the optical communications are the transmitting and receiving telescopes, laser, narrowband filters, avalanche photodiodes (APD), and the charge coupled devices (CCD) required for acquisition and tracking. All other devices associated with the optical communication system are normal electronics which are readily available.

The maturity assessment of the downlink laser was performed in a very conservative manner. The laser chosen for the L2 orbit is a 1 Watt laser operating at a wavelength of 860 nm.<sup>2</sup> This wavelength was chosen to maximize the efficiency of silicon detectors. The laser itself is a solid state device whose output is amplified by a master oscillator phased amplifier (MOPA). A current SBIR program calls for a 1 Watt laser to be delivered within a year from SDL Inc. This laser will be capable of transmitting 10 Gbit/sec at a wavelength of 980 nm. The configuration is also a laser diode with a MOPA. Hence, obtaining the predicted performance by 2003 should not be a challenge. The pulsed Nd:YAG laser used for the drift orbits and the 1x3 AU orbit was modeled after a laser produced by McDonnell Douglas Astronautics Co. as part of a Department of

<sup>4</sup> Private discussion with Keith Wilson at JPL.

Defense program in the mid 1980s. The proposed laser for the NGST program will have an output power of 3 Watts with a pulse width of 10 nsec operating with a pulse repetition frequency (PRF) of 1 MHz.<sup>3</sup> The laser produced by McDonnell Douglas had an output power of 1 Watt while operating at a PRF of 1 MHz. Current uplink laser technology provides roughly 200 Watts of power out of a single laser. By the year 2003 an output power of 500 Watts is projected. Thus, multiple lasers will be required to achieve 1 kW power necessary for the 1x3 AU orbit uplink, whereas a single laser will be sufficient for all other cases.

The APD's used for the FOCAS simulation are devices which are currently available. Data sheets were used to obtain all necessary operation specifications required to perform an accurate analysis. The filters used for the analysis had a bandwidth of 1 nm with a transmission factor of 80%. Filter performance better than that specified is projected in JPL Publication 98-01 "Narrow-Band Filters for Optical Communications" [1]. The CCD proposed is a customized 128 by 128 pixel camera. A method by which to replace the CCD with an active pixel sensor (APS) is being developed.

## 11. Cost, Power, and Size

The section summarizes the cost, power, and size analysis of the proposed S/C systems. All data was obtained in a manner similar to that seen in Table III.2-2 of [3]. The values listed for the 35 cm telescope have been used as a worst case scenario for the proposed 30 cm system. Table 5 gives a summary of the size, cost, and power estimates. Even though the laser system proposed in [3] is a Q-switched laser, the cavity dumped laser proposed for NGST will have very similar power, size and cost characteristics. The efficiency of the laser has been assumed to be 10%, a figure characteristic of most cavity dumped lasers.

Telescope Diameter (cm)	30
Transmitter Power (W)	3.0
<b>Mass (kg)</b>	<b>16.5±1.7</b>
Laser Subsystem (Redundant)	8.8
Transmit/Receive Aperture	4.6
Acq/Trk/Ptg/Com Subsystem (Redund.)	0.7
Thermal/Mechanical	0.9
Other (Processor, ...)	1.5
<b>Power (W)</b>	<b>87.8±8.8</b>
Laser Subsystem	69.4
Transmit/Receive Aperture	0.5
Acq/Trk/Ptg/Com Subsystem	3.6
Thermal/Mechanical	0.5
Other (processor, ...)	13.8
First Flight Unit (NRE + RE) Cost (\$ M)	15.0
Second Flight Unit (RE) Cost (\$M)	8.0
Size (cm <sup>3</sup> )	40x45x60
Data Volume Capability (GB/day)	100

Table 5. Cost, power and mass estimate for 30-cm S/C aperture system (with modifications from Hemmati, et al [3]).

The system proposed for the L2 is a smaller 10-cm aperture. The estimates for the proposed NGST system are the estimates for the 10-cm system listed in [3]. A major difference in the between the system in [3] and the proposed system is that the transmitting laser for NGST is a solid state laser with a MOPA instead of a Q-switched pumped laser. The estimate for the MOPA configuration is completely different from the Q-switched system proposed in [3]. The efficiency of the MOPA is about 15% to 20%. Unlike the case for the 30 cm aperture, only a single transmitting laser is required (i.e. two circularly polarized are not necessary), thus there are only two lasers housed in this system instead of four. Table 6 shows the estimates obtained for the 10-cm S/C aperture.

Telescope Diameter (cm)	10
Transmitter Power (W)	1.0
<b>Mass (kg)</b>	<b>6.4±0.9</b>
Laser Subsystem (Redundant)	2.1
Transmit/Receive Aperture	1.3
Acq/Trk/Ptg/Com Subsystem (Redund.)	0.7
Thermal/Mechanical	0.8
Other (Processor, ...)	1.5
<b>Power (W)</b>	<b>20.2±7</b>
Laser Subsystem	5.0
Transmit/Receive Aperture	0.5
Acq/Trk/Ptg/Com Subsystem	3.6
Thermal/Mechanical	0.5
Other (processor, ...)	10.6
First Flight Unit (NRE + RE) Cost (\$ M)	12.80
Second Flight Unit (RE) Cost (\$M)	4.8
Size (cm <sup>3</sup> )	15x15x30
Data Volume Capability (GB/day)	100

Table 6. Cost, power and mass estimate for 10-cm S/C aperture system  
(with modifications from Hemmati et al [3]).

The optical system also requires the use of gimbal. The size current gimbal used to test the Optical Communications Demonstrator approximately 2 feet tall with a diameter of 12-in. The weight of the gimbal is 10 Kg. The peak power necessary to drive the motors is 80 Watts. This power is not continuously used, it is only necessary for short periods lasting only a few seconds. A more efficient gimbal could be used to replace the existing one. Whereas the size would be comparable, necessary power would drop to roughly 50 Watts.

If the orbit geometry and spacecraft orientation are favorable a gimballed flat may be used in place of a gimbal. This could be the case for the drift orbits and the 1X3 AU orbit. The geometry of the L2 orbit will not permit the use of a gimballed flat. The size of a gimballed flat for all other orbits would be approximately 14-in tall with a diameter of 24-in. Mass of the flat would be roughly 10 kg. The power consumption of the device would be 8 Watts in the quiescent mode and 22 Watts in the active mode.

## 12. XV. Acknowledgements

The author is indebted to M. Jeganathan, H. Hemmati, K. Wilson, J. Lesh, J. Sandusky, and G. Ortiz for many stimulating and fruitful discussions.

## 13. References

1. N. E. B. Zellner, "Narrow-Band Filters for Optical Communications", JPL Publication 98-01.
2. A. Del Castillo, JPL Interoffice Memorandum, 331.3-98-21.
3. H. Hemmati, et al., "Comparative Study of Optical and RF Communication Systems for a Mars Mission- Part I, Overall System and Link Design", JPL TDA Progress Report 42-128.

## 14. Appendix A. MODTRAN

This appendix contains the MODTRAN figure used to determine the background radiance as a function of Sun-Earth-Probe angle. All values used were either read directly off the figure or interpolated using the nearest available angle.

